Top Theory - Resummed Calculations

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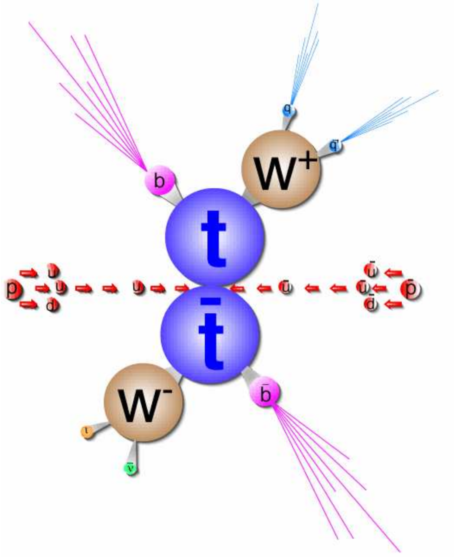
DESY Zeuthen, June 16, 2011

Outline

1. Top-Quark Pair Production at Hadron Colliders
2. Resummation and Approximate NNLO Results
3. Observables

Top Quark Pair Production



Top Quark Pair Production

Key measurements at the Tevatron and the LHC include the top-quark pair production total cross section and differential distributions

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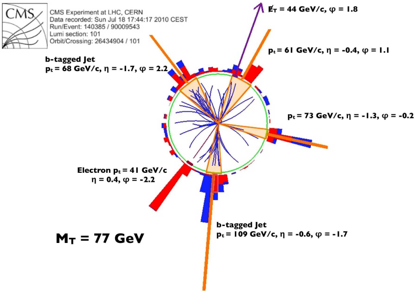
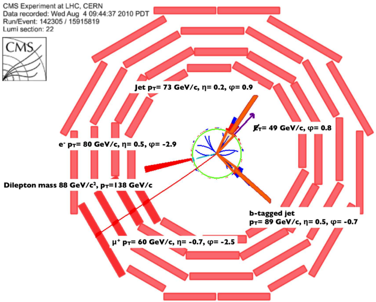
The top quarks decay almost exclusively in a W boson and a b quark. The observed processes are

$$\begin{aligned} p\bar{p}, pp \to t\bar{t}X &\to l_1^+ + l_2^- + j_b + j_{\bar{b}} + p_T^{\text{miss}} + (n \geq 0) \quad \text{jets} \\ p\bar{p}, pp \to t\bar{t}X &\to l_1^\pm + j_b + j_{\bar{b}} + p_T^{\text{miss}} + (n \geq 2) \quad \text{jets} \\ p\bar{p}, pp \to t\bar{t}X &\to j_b + j_{\bar{b}} + (n \geq 4) \quad \text{jets} \end{aligned}$$

All these channels were observed and analyzed at the Tevatron

TOP-PAIR PRODUCTION AND THE LHC





- Next 2 years at the LHC
  $\sim$ few 10^4 top pair events
- Fall 2010: First measurement of the total CS at ATLAS and CMS
- June 2011: CMS $36\,\mathrm{pb}^{-1}$
  (Di-lepton channel)

$$\sigma^{t\bar{t}} = 168 \pm 18 \pm 14 \pm 7\,\mathrm{pb}$$

arXiv:1105.5661

(Leptons + jets channel)

$$\sigma^{t\bar{t}} = 173^{+39}_{-32}\,\mathrm{pb}$$

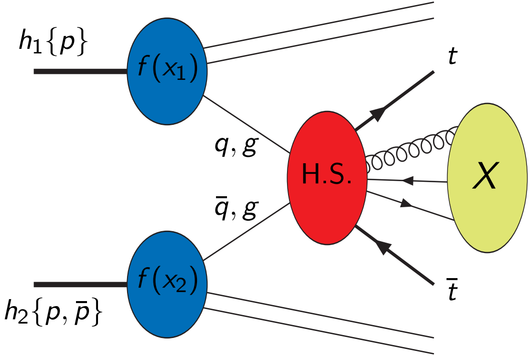
arXiv:1106.0902

ATLAS $35\,\mathrm{pb}^{-1}$ (prelim.)

$$\sigma^{t\bar{t}} = 180 \pm 9 \pm 15 \pm 6\,\mathrm{pb}$$

Top Quark Pair Hadroproduction

Top-quark pair production is a hard scattering process which can be computed in perturbative QCD

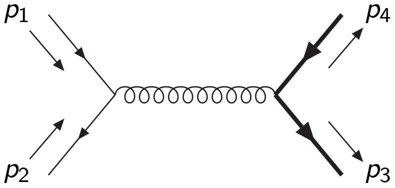


$$d\sigma^{t\bar{t}}_{h_1,h_2} = \sum_{i,j=q\bar{q}g} \int dx_1 dx_2 f_i^{h_1}(x_1, \mu_F) f_j^{h_2}(x_2, \mu_F) d\hat{\sigma}_{ij}(s, m_t, \alpha_s(\mu_R), \mu_F, \mu_R)$$

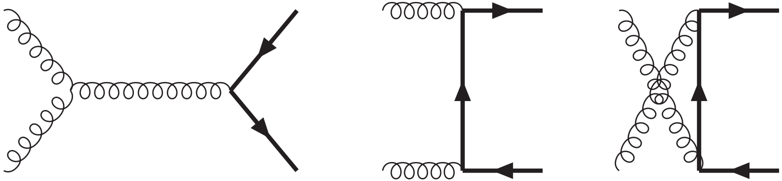
$$s_{\text{had}} = (p_{h_1} + p_{h_2})^2 \ , \ s = x_1 x_2 s_{\text{had}}$$

Tree Level QCD Partonic Processes

$$q(p_1) + \bar{q}(p_2) \longrightarrow t(p_3) + \bar{t}(p_4)$$



$$g(p_1) + g(p_2) \longrightarrow t(p_3) + \bar{t}(p_4)$$



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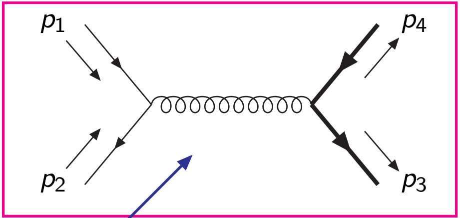

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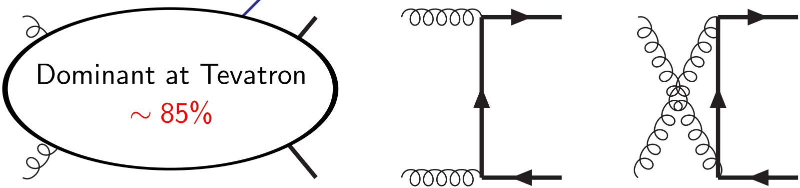

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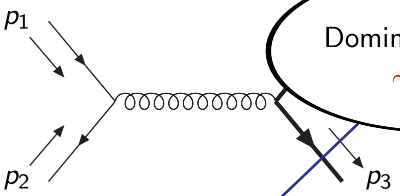
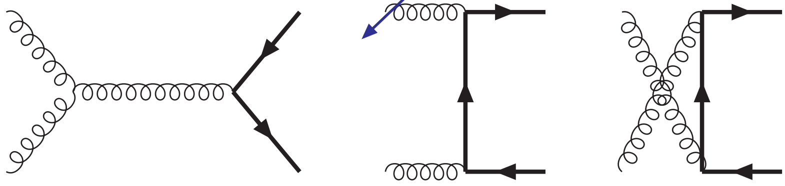


Dominant at LHC
$\sim 90\%$

$$g(p_1) + g(p_2) \longrightarrow t(p_3) + \bar{t}(p_4)$$



NLO Corrections

perturbative expansion:

$$d\hat{\sigma}_{ij} = \alpha_s^2 d\hat{\sigma}_{ij}^{(0)} + \alpha_s^3 d\hat{\sigma}_{ij}^{(1)} + \alpha_s^4 d\hat{\sigma}_{ij}^{(2)} + \cdots$$

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The NLO corrections to top-quark pair production have been a subject of active research for more than 20 years
(too many authors to list here!)

- NLO QCD corrections to the total cross section
- NLO QCD corrections to the distributions (p_T, rapidity, invariant mass, . . .)
- Mixed QCD-EW corrections
- NLO with top decays in narrow width approximation
- NLO with top decays with off-shell top quarks (recent results by Denner *et al.* arXiv:1012.3975, and Bevilacqua *et al.* arXiv:1012.4230)
- Beyond fixed order calculations: NLL resummation of threshold effects

Resummation

From a lecture by E. Laenen

Resummation = organization of large logarithms in perturbative expansion

$$\begin{aligned}\hat{O} &= \overbrace{\underbrace{1+\alpha_s(L^2+L+1)}_{}}^{}\! \end{aligned}$$

$$\begin{aligned}\hat{O} &= \overbrace{\overbrace{1+\alpha_s(L^2+L+1)}^{NLO}+\alpha_s^2(L^4+L^3+L^2+L+1)}^{NNLO}+\mathcal{O}(\alpha_s^3)\\ &= \exp\Big(\underbrace{\underbrace{Lg_1(\alpha_s L)}_{LL}+g_2(\alpha_s L)}_{NLL}+\alpha_s g_3(\alpha_s L)+\cdots\Big)\,\underbrace{C(\alpha_s)}_{\text{constants}}\\ &\quad +\text{suppressed terms}\end{aligned}$$

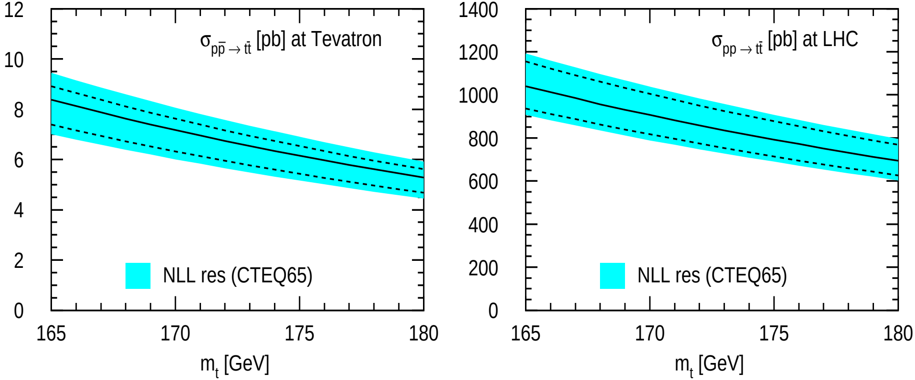
$L = \ln\left(\frac{\text{"high" scale}}{\text{"low" scale}}\right)$ The arguments depends on the observable

Resummation reduces the theoretical uncertainties on a given observable

Uncertainty on the NLO+NLL Cross Section

The partonic cross sections involve terms like $\ln(1-4m^2/s)$ which become large near threshold and must be resummed

Berger, Contopanagos ('95-'98), Kidonakis, Sterman ('97), Bonciani *et al.* ('98), Kidonakis *et al.* ('01), Kidonakis, Vogt ('03), Banfi, Laenen ('05), Cacciari *et al* ('08) Czakon *et al* ('09)



S. Moch and P. Uwer ('08)

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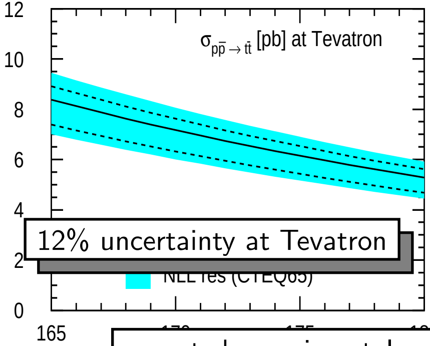
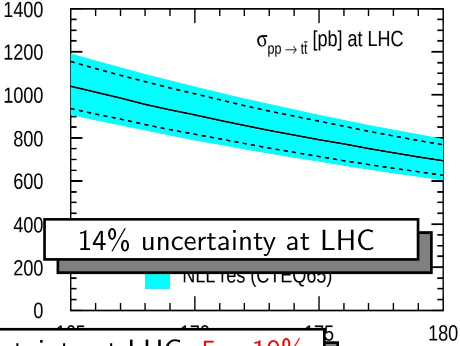


12% uncertainty at Tevatron



14% uncertainty at LHC

expected experimental uncertainty at LHC $5 - 10\%$

S. Moch and P. Uwer ('08)

Beyond NLO+NLL

In order to take full advantage of the LHC potential, one needs to obtain theoretical predictions that go
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Full NNLO Calculations

Calculations are carried out in a perturbative expansions in powers of α_s

Goal: calculate all of the corrections of $\mathcal{O}(\alpha_s^2)$ (NNLO) to the tree-level process

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NNLL Resummation Approximate NNLO

Not all corrections of order α_s^n have the same relevance

Large logarithms $\ln(r) \sim 1/\alpha_s$ are present

Goal: to resum corrections $\propto \alpha_s^n \ln^m(r)$ to all orders in α_s

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this talk

Full NNLO Calculations	**NNLL Resummation Approximate NNLO**
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NNLL Resummation

in collaboration with

V. Ahrens, M. Neubert, B. Pecjak, and L. L. Yang

arXiv:1105. 5824[hep-ph]
arXiv:1103.0550 [hep-ph]
JHEP 1009 (2010) 097 (arXiv:1003.5827 [hep-ph])
Phys.Lett. B687 (2010) 331-337 (arXiv:0912.3375 [hep-ph])

Soft Limits

partonic process:

$$p_i(p_1) + p_j(p_2) \longrightarrow t(p_3) + \bar{t}(p_4) + X(k) \qquad (i, j \in \{q, \bar{q}, g\})$$

Name	Observable	Soft Variable
Production Threshold	σ	$\beta = \sqrt{1 - \frac{4m_t^2}{s}}$
Single Particle Inclusive (1PI)	$\frac{d\sigma}{dp_T\, dy}$	$s_4 = (p_4 + k)^2 - m_t^2$
Pair Invariant Mass (PIM)	$\frac{d\sigma}{dM_{t\bar{t}}\, d\cos\theta}$	$(1 - z) = 1 - \frac{M_{t\bar{t}}^2}{s}$

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parto

Large logarithms appear in the partonic cross section if the "soft variable" is small

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$\beta \to 0$ is a special case of 1PI and PIM and $\langle\beta\rangle \sim 0.5$

$\Longrightarrow$ we focused on PIM and 1PI kinematics

Factorization

In PIM, in the limit $z \to 1$ (threshold region) there are three different scales

$$s, M^2, m_t^2 \gg s(1-z)^2 \gg \Lambda_{\text{QCD}}^2$$

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In the threshold region the partonic cross section factors into hard functions and soft functions (matrices in color space)

Kidonakis, Sterman ('97)

$$d\hat{\sigma} \sim \text{Tr}\left[\mathbf{H}(M, m_t, \cos\theta, \mu)\mathbf{S}(\sqrt{s}(1-z), m_t, \cos\theta, \mu)\right]$$

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Kidonakis, Sterman ('97)

H $\to$ virtual corrections, same for PIM and 1PI

S $\to$ real corrections, different in PIM and 1PI

H and **S** satisfy RG equations

which one can solve to resum large corrections

Th ... of

Resummed Formulas

$$d\hat{\sigma} \propto \exp\left[4a_{\gamma^\phi}(\mu_s, \mu_f)\right] \mathrm{Tr}\left[\mathbf{U}(\mu_h, \mu_s)\,\mathbf{H}(\mu_h)\,\mathbf{U}^\dagger(\mu_h, \mu_s)\tilde{\mathbf{s}}\,(\partial_\eta, \mu_s)\right] \frac{e^{-2\gamma_E \eta}}{\Gamma(2\eta)} \lambda^{-1+2\eta}$$

E_s = energy of the soft radiation / depends on the distribution

$$2E_s \equiv m_t \lambda = m_t \underbrace{\frac{s_4}{m_t\sqrt{s_4 + m_t^2}}}_{\lambda_{1\mathrm{PI}_{\mathrm{SCET}}}} \qquad 2E_s \equiv M\lambda = M_{t\bar{t}} \underbrace{\frac{1-z}{\sqrt{z}}}_{\lambda_{\mathrm{PIM}_{\mathrm{SCET}}}}$$

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Resummed Formulas

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RG-impr. PT	log accuracy	Γ_{cusp}	γ^h, γ^ϕ	$\mathbf{H}$, $\tilde{\mathbf{s}}$
LO	NLL	2-loop	1-loop	tree-level
NLO	NNLL	3-loop	2-loop	1-loop

All the pieces for the NNLL calculation are now available

Ahrens, AF, Neubert, Pecjak, and Yang ('10-'11)

Approximate NNLO

The resummed formulas can be re-expanded

$$d\hat{\sigma}_{\mathrm{NNLO}} = D_3 P_3(\lambda) + D_2 P_2(\lambda) + D_1 P_1(\lambda) + D_0 P_0(\lambda) + C_0 \delta(\lambda) + R(\lambda)$$

with

$$P_n(z) = \left[\frac{\ln^n(1-z)}{(1-z)}\right]_+ \qquad P_n(s_4) = \left[\frac{\ln^n(s_4/m_t^2)}{s_4}\right]_+$$

- It was possible to calculate D_3, D_2, D_1, D_0 and the scale dependence of C_0 (D_3, D_2, D_1 first obtained by Kidonakis, Leanen, Moch, and Vogt ('01))
- Keeping the exact form of the energy re-organizes the threshold expansion, so that some formally subleading terms are kept compared to other calculations (Kidonakis et.al.), which use PIM and 1PI

$$\frac{\ln(z)}{1-z} \quad \text{in } \mathrm{PIM}_{\mathrm{SCET}} \qquad \frac{\ln\left(1+\frac{s_4}{m_t^2}\right)}{s_4} \quad \text{in } \mathrm{1PI}_{\mathrm{SCET}}$$

Dynamical Threshold Enhancement

Does the soft limit provide a good approximation of the exact result?
ex. invariant mass distribution

$$z = \frac{M^2}{s} \qquad \tau = \frac{M^2}{s_{\text{had}}}$$

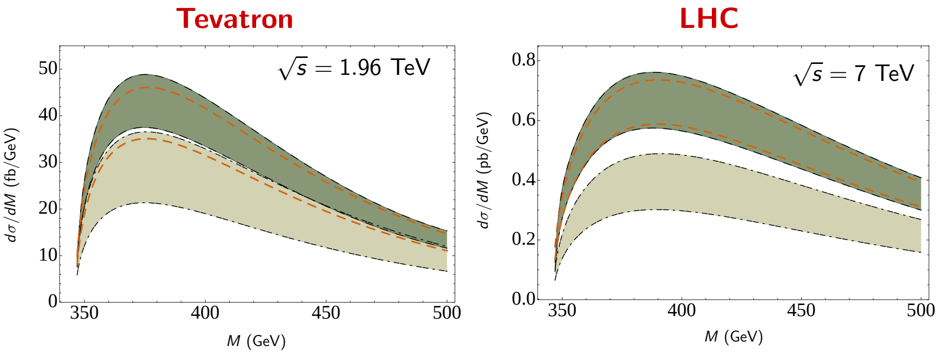
$$\frac{d\sigma}{dM} = \frac{8\pi\beta}{3M} \int_\tau^1 \frac{dz}{z} \sum_{ij=(q\bar{q},gg,\bar{q}q)} \overbrace{ff_{ij}\left(\frac{\tau}{z},\mu\right)}^{\text{parton luminosity}} \underbrace{C_{ij}\left(z,\ldots,\mu\right)}_{\text{partonic distribution}}$$

The limit $z \to 1$ provides a good approximation to the complete result if

a) $\tau \sim 1$; ...but the interesting region is $\tau < 0.3$

b) $ff_{ij} \to 0$ for $z \to \tau$; Dynamical Threshold Enhancement

Dynamical Threshold Enhancement

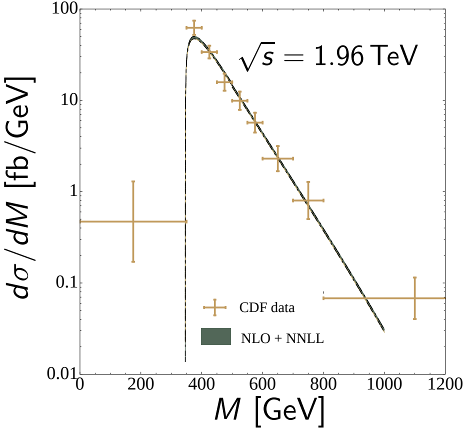


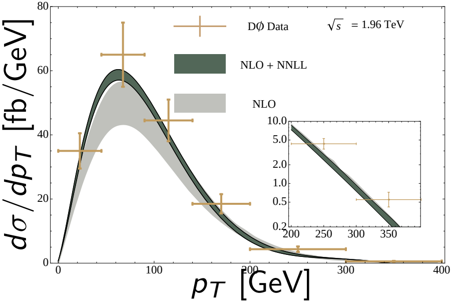
- Exact NLO result (dark grey band) obtained with MCFM (Campbell, Ellis)
- The NLO threshold expansion $\longrightarrow$ band between the dashed lines ($200\,\text{GeV} \leq \mu \leq 800\,\text{GeV}$; close to $M/2 \leq \mu \leq 2M$)
- The threshold expansion agrees quite well with the exact result, even in the low invariant mass region

Observables

Differential Cross Sections,
Total Cross Section,
Forward-Backward Asymmetry

Invariant Mass Distribution and p_T Distribution Versus Tevatron Data





Normalization and shape of the distributions are consistent with data

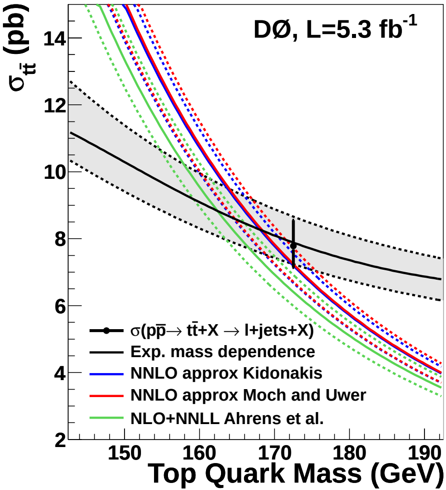
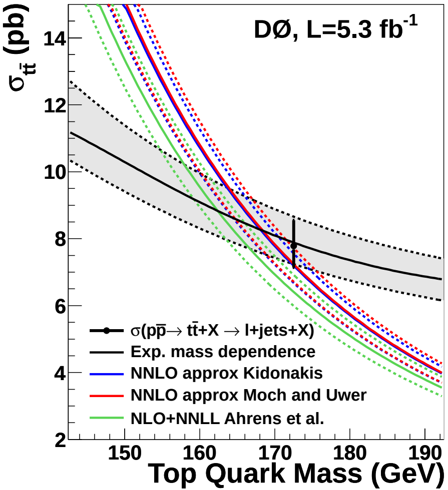


Figure from D0 in lepton +jets channel, arXiv:1101.0124

- Measured at the Tevatron and at the LHC
- Comparison theory/experiments can be used to extract m_t [Langenfeld *et al*, ('09), D0 ('11)]

The Total Inclusive Cross Section



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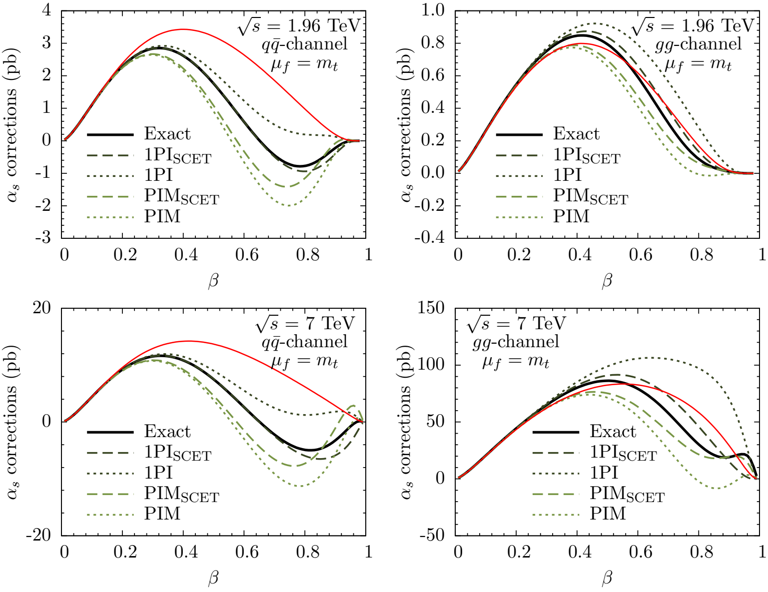
- Measured at the Tevatron and at the LHC
- Comparison theory/experiments can be used to extract m_t [Langenfeld *et al*, ('09), D0 ('11)]
- Can be calculated by integrating the differential distributions WARNING: different soft limit neglect different types of power corrections

The β Distribution and the Total CS

$$\frac{d\sigma}{d\beta} = \frac{1}{s}\frac{8\beta}{(1-\beta^2)^2}\sum_{ij}\underbrace{f\!f_{ij}\left(\frac{s}{s_{\mathrm{had}}},\mu_f\right)}_{\text{parton luminosities}}\alpha_s^2\underbrace{f_{ij}\left(\frac{4m_t^2}{s},\mu_f\right)}_{\text{partonic c. s.}} \qquad s = \frac{4m_t^2}{(1-\beta^2)}$$

- Can be calculated both from PIM and 1PI kinematics, or directly for $\beta \to 0$ [Langenfeld *et al*, Czakon *et al*, Beneke *et al* ('09)]
- For $\beta \to 0$ gluon emission is soft, 1PI, PIM, and exact QCD must agree
- For larger β, different calculational schemes neglect different kinds of power corrections: it is interesting to compare the various approximations with the exact result at NLO

PIM vs. 1PI at NLO

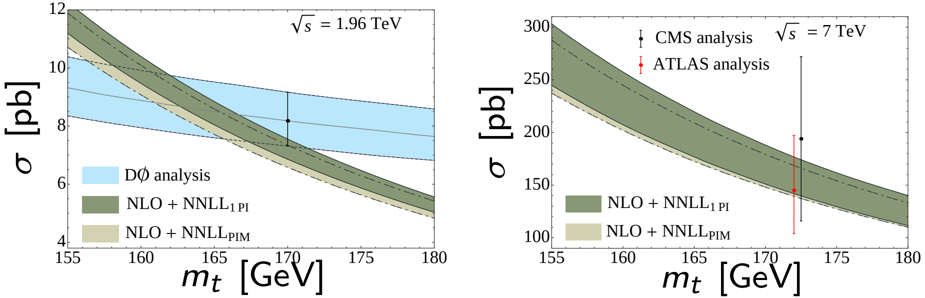


The Total Cross Section in Different Schemes

$m_t/2 < \mu_f < 2m_t$, $m_t = 173.1\,\text{GeV}$, MSTW2008 pdfs, only scale uncertainties

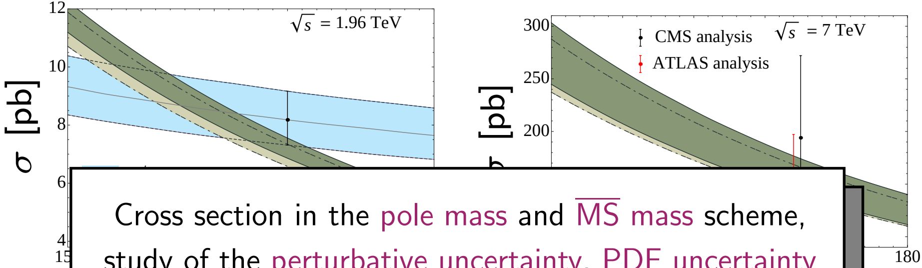
(c. s. in pb)	Tevatron	LHC (7 TeV)
$\sigma_{\text{NLO},q\bar{q}+gg}$	$6.80^{+0.27}_{-0.73}$	160^{+5}_{-15}
$\sigma_{\text{NLO leading}}$ 1PI_{SCET}, (1PI)	$6.79^{+0.20}_{-0.70}$ $(7.23^{+0.45}_{-0.86})$	163^{+0}_{-11} (183^{+6}_{-18})
$\sigma_{\text{NLO leading}}$ PIM_{SCET}, (PIM)	$6.42^{+0.42}_{-0.76}$ $(6.20^{+0.28}_{-0.69})$	152^{+7}_{-15} (143^{+1}_{-12})
$\sigma_{\text{NNLO approx}}$ 1PI_{SCET}, (1PI)	$6.63^{+0.00}_{-0.27}$ $(7.06^{+0.00}_{-0.29})$	155^{+3}_{-2} (180^{+3}_{-8})
$\sigma_{\text{NNLO approx}}$ PIM_{SCET}, (PIM)	$6.62^{+0.05}_{-0.40}$ $(6.46^{+0.18}_{-0.45})$	155^{+8}_{-8} (148^{+14}_{-11})
$\sigma_{\text{NLO+NNLL}}$, 1PI_{SCET}	$6.55^{+0.16}_{-0.14}$	150^{+7}_{-7}
$\sigma_{\text{NLO+NNLL}}$, PIM_{SCET}	$6.46^{+0.18}_{-0.19}$	147^{+7}_{-6}

- PIM and 1PI do not agree well with each other Kidonakis, Laenen, Moch, Vogt ('01); Kidonakis ('10)
- PIM_{SCET} and 1PI_{SCET} are consistent with each other and exact result at NLO Ahrens, AF, Neubert, Pecjak, Yang ('10, '11)
- NLO+NNLL and approximate NNLO consistent with each other



- The theoretical predictions include scale and PDF uncertainties, $\mu_f = 400\,\text{GeV}$ in the figure
- 1PI_{SCET} and PIM_{SCET} give consistent results averages $\sigma_{\text{TEV}} = 6.63^{+0.07+0.63}_{-0.41-0.48}$ pb , $\sigma_{\text{LHC}}(7\,\text{TeV}) = 155^{+8+14}_{-9-14}$ pb (approx. NNLO, MSTW2008 PDFs, $\mu_f = m_t$, scale uncertainty, PDFs + α_s)

THE TOTAL CROSS SECTION



Cross section in the pole mass and $\overline{\text{MS}}$ mass scheme, study of the perturbative uncertainty, PDF uncertainty and PDF dependence, and simple fits for NNLO approx. calculations of $\sigma(m_t)$ in arXiv:1105.5824

- 1PI$_{\text{SCET}}$ and PIM$_{\text{SCET}}$ give consistent results
  averages $\sigma_{\text{TEV}} = 6.63^{+0.07+0.63}_{-0.41-0.48}$ pb , $\sigma_{\text{LHC}}(7\,\text{TeV}) = 155^{+8+14}_{-9-14}$ pb
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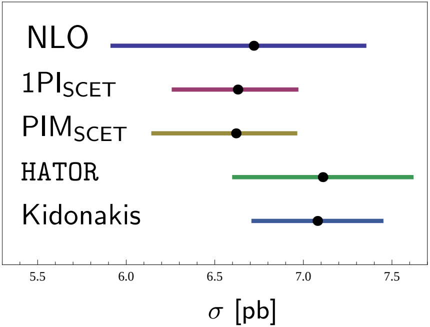
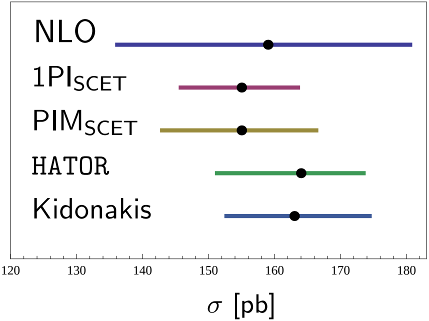
$mt = 173.1$ GeV, $mt/2 < \mu_f = \mu_r < 2mt$, MSTW2008 90% CL
PDF and scale uncertainties added in quadrature

Tevatron



LHC 7 TeV



- $1PI_{SCET}$ and PIM_{SCET} NNLO approx. calculations Ahrens *et al* '10, '11
- Kidonakis: NNLO approx 1PI formulas ($m_t = 173$ GeV) Kidonakis ' 10
- HATOR: production thereshld formulas Aliev *et al* '10

The Forward-Backward Asymmetry at the Tevatron

The forward-backward asymmetry originates from the difference in the top-quark production rates in the forward and backward hemisphere in $p\bar{p}$ collisions

$$A_{\rm FB}^{i} \equiv \frac{N(y_t^i \geq 0) - N(y_t^i \leq 0)}{N(y_t^i \geq 0) + N(y_t^i \leq 0)}$$

- The measured asymmetry in the lab frame (CDF 5.3 fb^{-1})

$$A_{\rm FB}^{p\bar{p}} = 0.150 \pm 0.050\,\text{stat} \pm 0.024\,\text{syst}$$

- The measurements in the $t\bar{t}$ frame are

$$\begin{aligned} A_{\rm FB}^{t\bar{t}} &= 0.158 \pm 0.072\,\text{stat} \pm 0.017\,\text{syst} \quad (\text{CDF} \quad 5.3\,\text{fb}^{-1}) \\ A_{\rm FB}^{t\bar{t}} &= 0.08 \pm 0.04\,\text{stat} \pm 0.01\,\text{syst} \quad (\text{D0} \quad 4.3\,\text{fb}^{-1}) \end{aligned}$$

The Forward-Backward Asymmetry at the Tevatron

The forward-backward asymmetry originates from the difference in the top-qua ... in $p\bar{p}$ collision

AFNPY ('10) partonic frame	$A_{\rm FB}$ $(\mu_f = m_t)$	$A_{\rm FB}$ $(\mu_f = 400\,\text{GeV})$
"LO" QCD	$0.074^{+0.007}_{-0.006}$	$0.067^{+0.005}_{-0.005}$
"LO" + NNLL	$0.073^{+0.011}_{-0.007}$	$0.066^{+0.006}_{-0.005}$

$A_{\rm FB}^{t\bar{t}} = 0.076^{+0.008}_{-0.005}$ LO QCD ; $A_{\rm FB}^{t\bar{t}} = 0.080^{+0.007}_{-0.005}$ LO QCD + EW

Bernreuther and Si ('10)

- Th

- The measurements in the $t\bar{t}$ frame are

$$A_{\rm FB}^{t\bar{t}} = 0.158 \pm 0.072\,\text{stat} \pm 0.017\,\text{syst} \quad (\text{CDF} \quad 5.3\,\text{fb}^{-1})$$
$$A_{\rm FB}^{t\bar{t}} = 0.08 \pm 0.04\,\text{stat} \pm 0.01\,\text{syst} \quad (\text{D0} \quad 4.3\,\text{fb}^{-1})$$

The Forward-Backward Asymmetry at the Teva

The for ... he

top-qua ... in $p\bar{p}$

collisio

AFNPY ('11) Laboratory frame	$A_{\rm FB}$ $(\mu_f = m_t)$	$A_{\rm FB}$ $(\mu_f = 400\,\mathrm{GeV})$
"LO" QCD	$0.048^{+0.005}_{-0.004}$	$0.044^{+0.004}_{-0.003}$
"LO" + NNLL	$0.049^{+0.002}_{-0.002}$	$0.046^{+0.003}_{-0.003}$

The predicted LO asymmetry is $A_{\rm FB}^{p\bar{p}} = 0.051^{+0.007}_{-0.003}\,\%$

Kühn and Rodrigo ('08), Bernreuther and Si ('10)

- The measured asymmetry in the lab frame (CDF 5.3 fb^{-1})

$$A_{\rm FB}^{p\bar{p}} = 0.150 \pm 0.050\,\mathrm{stat} \pm 0.024\,\mathrm{syst}$$

- The measurements in the $t\bar{t}$ frame are

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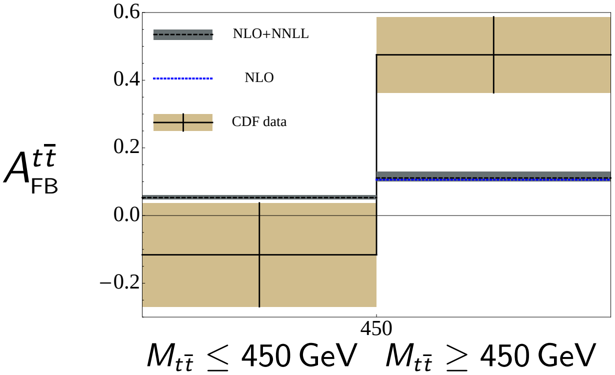
$$A^{t\bar{t}} = 0.08 \pm 0.04\,{\rm stat} \pm 0.01\,{\rm syst} \quad ({\rm D0} \quad 4.3\,{\rm fb}^{-1})$$

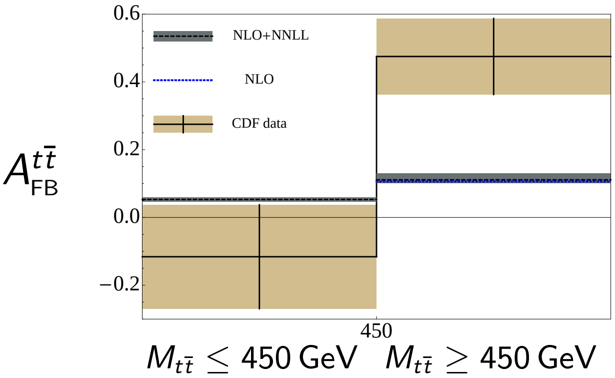
Theory and experiment agree at about 2σ

Invariant Mass Dependent Asymmetry



$$A_{\rm FB}^{t\bar{t}}(m_1, m_2) = \frac{\int_{m_1}^{m_2} dM_{t\bar{t}} \left[\left(\frac{d\sigma}{dM_{t\bar{t}}} \right)_{\rm F} - \left(\frac{d\sigma}{dM_{t\bar{t}}} \right)_{\rm B} \right]}{\int_{m_1}^{m_2} dM_{t\bar{t}} \left[\left(\frac{d\sigma}{dM_{t\bar{t}}} \right)_{\rm F} + \left(\frac{d\sigma}{dM_{t\bar{t}}} \right)_{\rm B} \right]}$$

Invariant Mass Dependent Asymmetry



- Measured in the $t\bar{t}$ frame CDF arXiv:1101.0034
- $M_{t\bar{t}} \leq 450$ GeV: compatible with LO within 1σ
- $M_{t\bar{t}} \geq 450$ GeV: larger than LO by 3.4σ
- Higher order corrections are not the answer (V. Ahrens *et al* preliminary)

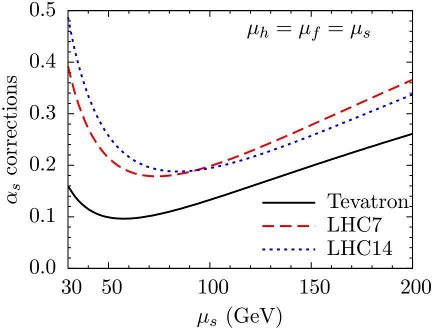
Summary & Conclusions

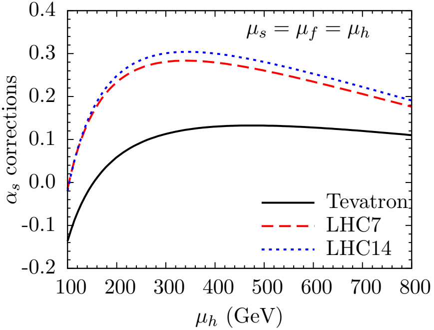
- Top pairs at the LHC $\Longrightarrow$ need to go beyond NLO+NLL accuracy
- NNLL Resummed /Approximate NNLO results for double differential distributions are available in two different threshold limits: 1PI_{SCET} and PIM_{SCET}. The two approaches kinematic schemes provide consistent results
- Phenomenology: the NNLL resummed / approximate NNLO results used to obtain predictions for
  - Total Cross Section
  - Forward-Backward Asymmetry
  - FB Asymmetry for $M_{t\bar{t}} \geq 450$ GeV

Backup Slides

Scales in the Resummed Cross Section

1PI kinematics, total cross section

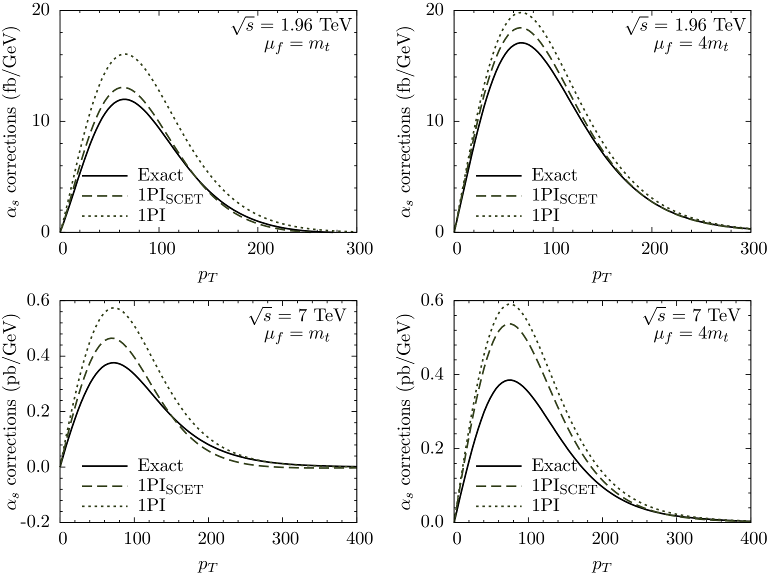




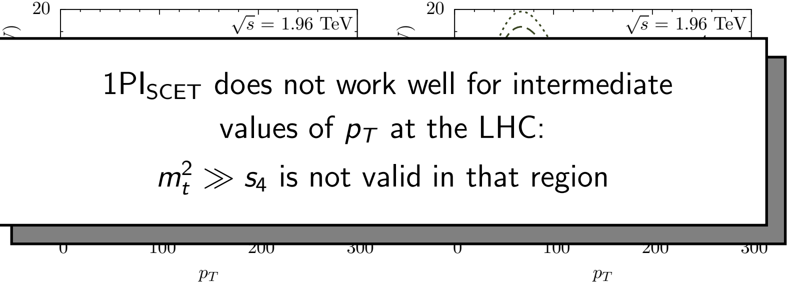
NLO corrections (%) from soft function: $\mu_s \sim 50 - 90\,\text{GeV}$

NLO corrections (%) from hard function: $\mu_h \sim 400\,\text{GeV}$

P_T Distribution at the LHC

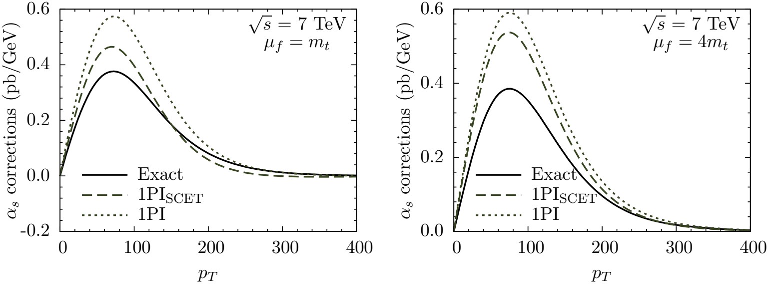


P_T Distribution at the LHC



1PI_{SCET} does not work well for intermediate values of p_T at the LHC:

$m_t^2 \gg s_4$ is not valid in that region



Total Cross Section Tables

POLE MASS	Tevatron		LHC7	
	MSTW	CTEQ	MSTW	CTEQ
LO	$6.66^{+2.95+(0.34)}_{-1.87-(0.27)}$	$5.45^{+2.16+0.33(0.29)}_{-1.42-0.27(0.24)}$	$122^{+49+(6)}_{-32-(7)}$	$100^{+35+9(7)}_{-24-8(7)}$
NLO	$6.72^{+0.41+0.47(0.37)}_{-0.76-0.45(0.24)}$	$6.77^{+0.40+0.50(0.43)}_{-0.74-0.40(0.34)}$	$159^{+20+14(8)}_{-21-13(9)}$	$148^{+18+13(11)}_{-19-12(10)}$
NNLO app.	$6.63^{+0.07+0.63(0.33)}_{-0.41-0.48(0.25)}$	$6.91^{+0.09+0.53(0.46)}_{-0.44-0.43(0.36)}$	$155^{+8+14(8)}_{-9-14(9)}$	$153^{+8+13(11)}_{-8-12(10)}$

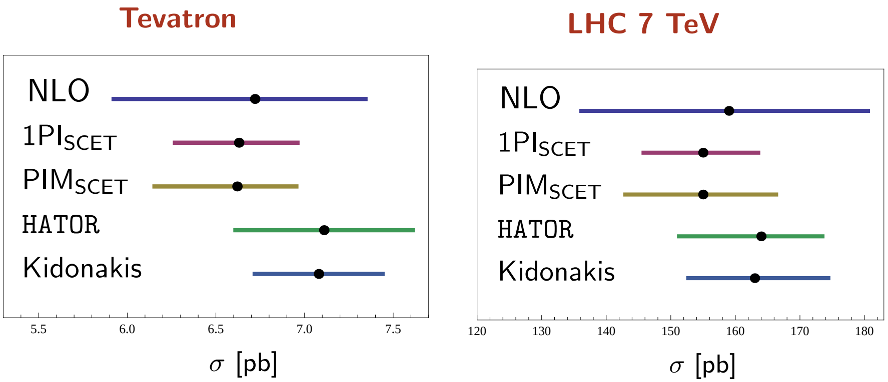
Total cross sections in pb for $m_t = 173.1$ GeV with MSTW2008 and CTEQ6.6 PDFs. The first error results from the perturbative uncertainty from both scale variations and the difference between PIM and 1PI kinematics, the second one accounts for the combined PDFs+α_s uncertainty. The numbers in parenthesis show the PDF uncertainty only.

$\overline{\text{MS}}$ MASS	Tevatron		LHC7	
	MSTW	CTEQ	MSTW	CTEQ
LO	$8.82^{+3.91+(0.44)}_{-2.48-(0.35)}$	$7.24^{+2.86+0.46(0.40)}_{-1.89-0.38(0.32)}$	$160^{+64+(8)}_{-42-(9)}$	$131^{+45+11(9)}_{-31-10(8)}$
NLO	$7.33^{+0.11+0.50(0.40)}_{-0.49-0.47(0.25)}$	$7.39^{+0.10+0.57(0.50)}_{-0.48-0.45(0.39)}$	$179^{+11+15(10)}_{-19-14(10)}$	$167^{+10+15(12)}_{-17-13(11)}$
NNLO app.	$6.64^{+0.11+0.58(0.33)}_{-0.40-0.43(0.23)}$	$6.92^{+0.12+0.52(0.46)}_{-0.43-0.42(0.37)}$	$157^{+9+13(8)}_{-9-13(9)}$	$154^{+9+13(11)}_{-9-12(10)}$

Total cross sections in pb in the $\overline{\text{MS}}$ scheme, for $\overline{m}(\overline{m}) = 164.1$ GeV. The first error results from the perturbative uncertainty from both scale variations and the difference between PIM and 1PI kinematics, the second one accounts for the combined PDFs+α_s uncertainty. The numbers in parenthesis show the PDF uncertainty only.

Comparisons

$mt = 173.1$ GeV, $mt/2 < \mu_f = \mu_r < 2mt$, MSTW2008 90% CL
PDF and scale uncertainties added in quadrature



- 1PI$_{SCET}$ and PIM$_{SCET}$ NNLO approx. calculations Ahrens *et al* '10, '11
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Comparisons

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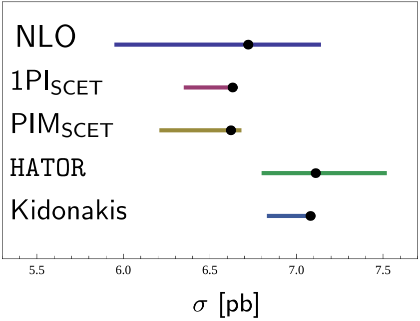
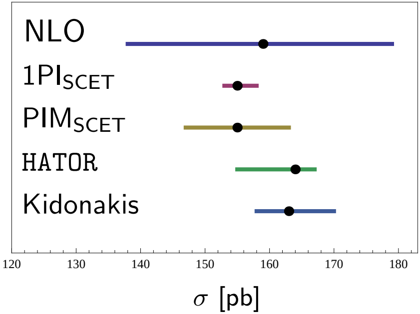
Only scale uncertainty

Tevatron



LHC 7 TeV



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